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Optoelectronic and Photonic Devices

for

Optical Communication Systems

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Optoelectronic and Photonics Devices for Optical Communication Systems

Abstract

General overview of optical communications was described. Efforts were concentrated for the reliability concerns of the optoelectronic and photonic parts needed for potential applications in space environments. Ultimate goal for this effort is to gradually establish enough data to develop a space qualification plan of newly developed specific parts using a numerical model to assess the lifetime and degradation of the devices hopefully for potential long term optical communications in space missions.

Optoelectronic and Photonics Devices for Optical Communication Systems

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Optoelectronic and Photonics Devices for Optical Communication Systems

INTRODUCTION

Recent progress and success in the fabrication of electrical and optical devices, such as the fundamental transverse-mode laser diodes, low loss optical fibers, and high quantum efficiency photodetectors, comprise a new and powerful class of monolithic integrated circuits for space optical communications. Such circuits are not only small in size, but also rugged and mechanically reliable. A single integrated optoelectronic circuit links electronic equipment and optical fibers. Since optical integration reduces parasitic reactance from electrical interactions, integrated devices are faster and less noisy. External electro-optic wave guide modulators should perform even faster modulations than possible with the laser diode.[1] The state-of-the-art in integrated optics will be described, with emphasis on space applications as well as the part problem areas which need to be resolved to further development.

Main degradation modes of the optical communication devices are described: dislocations that affect the inner region, metal diffusion and alloy reaction that affect the electrode, solder instability (reaction and migration) that affect the bonding parts, separation of metals in the heat sink bond, and defects in buried heterostructure devices are listed. These modes enhanced by current during ambient and high temperature operations are to examined. Facet damage due to oxidation is reported by light or moisture and is particular to laser diodes.[2]

Nominal data such as Quantum Efficiency, Frequency, and Operating Temperatures of selected manufacturers within their operation limit are listed for the Quick Review of the potential vendors. Ultimate goal for this effort is to gradually be established for enough data to develop a numerical model to assess the lifetime and degradation of optoelectronic devices in long term space missions.

A sub system of an integrated circuit performs a designed logic function needed in communications on a small chip such as silicon, gallium arsenide, or lithium niobate. On the chip, an array of active and passive components are fabricated and interconnected by various techniques. It offers great advantage in terms of small size, economy, and reliability for space applications because the circuit is generally encapsulated with only input, output, power supply, and control terminals accessible to other sub systems. The chips can become very small with improvements in materials and fabrication techniques. However, because of problems associated with interference among the high bit-rate electric signals in closely packed integrated circuits, further improvement had to wait for the development of tiny laser diodes and photodetectors.

To communicate from outer planets to Earth by means of a laser beam, one needs electrically efficient and compact lasers with an average output power and a pulse-repetition frequency (PRF) of greater than 2 W and 50KHz, respectively. Other important requirements are a single-spatial-mode beam quality, an output wavelength in the-visible-to-near-infrared range, short (nanosecond-level) pulse width, low pulse jitter, and simple thermal management. Fiber-coupled diode lasers facilitate the removal of heat generated by high-power diode pump lasers since the diode lasers can be cooled away from the laser resonator. Alignment of the pump lasers with the resonator is also simplified because the fiber delivers a manageable output from a 1-cm line source. Also, there are no complications resulting from thermal gradients in the laser's mechanical assembly caused by the diode pump lasers. Recently a number of cw and pulsed solid-state lasers pumped with cw diode lasers have been reported. Generation of greater than 11 W of cw output power at 1064 nm and greater than 3.5 W of a near-diffraction-limited 532 nm second-harmonic output at a PRF of 50 KHz were also reported.[3]

The development of the AlGaAs double heterostructure laser, which operates continuously (at 0.8-0.9 μm) at room temperature[4], and a quartz fiber with low loss (20 dB/Km) at the 0.8 μm wavelengths[5] were the beginning of the realization of the feasibility of fiber-optic communications, A great deal of recent research is emphasizing the development of long wavelength (1.2-1.6 μm) optical sources and detectors such as InGaAsP because of the very low loss (0.5 dB/Km) in single mode fibers.[6] Reduction of threshold current and transverse mode stabilization in 1.3 μm and 1.6 μm InGaAsP lasers has been achieved recently.[7] Lifetime of the device is estimated as greater than 10^5 hrs. at 50°C.[8] Thanks to the developments of suitable optical sources compatible

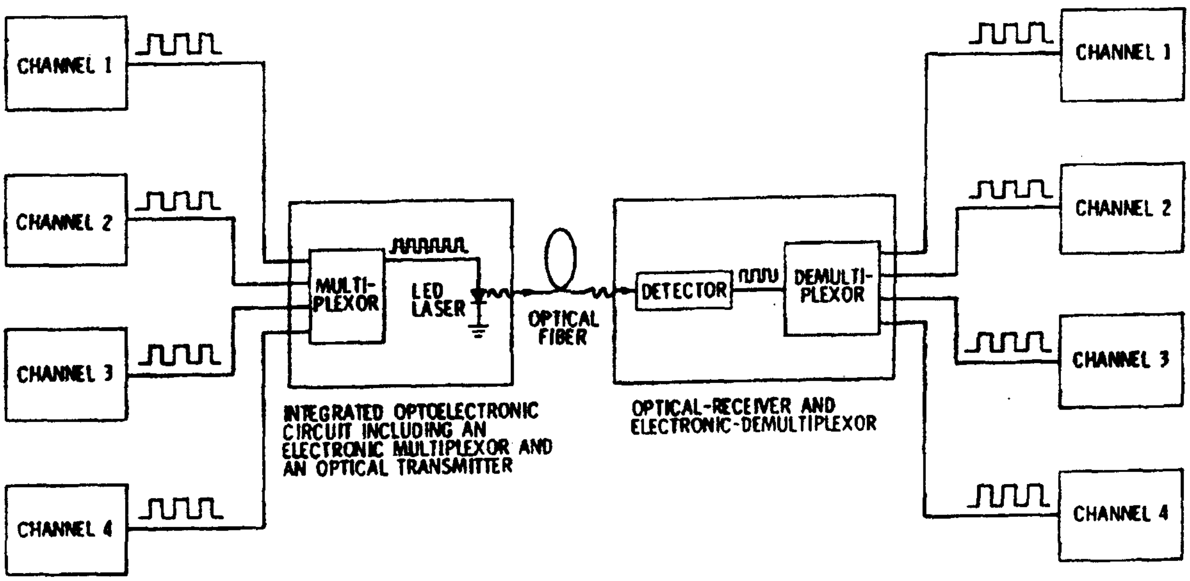

Figure 1. Of the two integrated optoelectronic shown, one is composed of an electronic multiplexer and a laser and the other of a multiplexer and a light detector, The circuits could link a number of electronic data channels to an optical fiber for transmitting data at a rate four times faster than that of each electronic channel.

with low loss optical fibers, a new powerful class of monolithically integrated circuits for optical communications is emerging which promises fast and reliable data transmission by a lightweight device at low cost. A single integrated optoelectronic circuit on a gallium arsenide chip can link electronic equipment and optical fibers, thereby replacing an elaborate interface with several parts. Thus far, all integrated circuits for space applications have been laboratory demonstrations, also commercial use will soon appear in the near future. One possibility is the monolithic integrated optoelectronic multiplexers and demultiplexers that would interface a digital signal source and an optical fiber as shown in Fig. 1. Because of the isolation between the microwave circuits and the input control signals, integrated optical devices would be less noisy. Furthermore, external electro-optic waveguide modulators using polarization insensitive operation can perform even higher frequency modulation, overcoming the difficulty of carrier lifetime limitations in the laser diodes as shown in Fig. 2.

All these facts have recently attracted the attention of many researchers to the use of optical signals to control solid state microwave signal devices. This report describes, briefly, recent developments in lasers, fibers, detectors, and waveguides, emphasizing applications, as well as the problem areas to be resolved for further development.

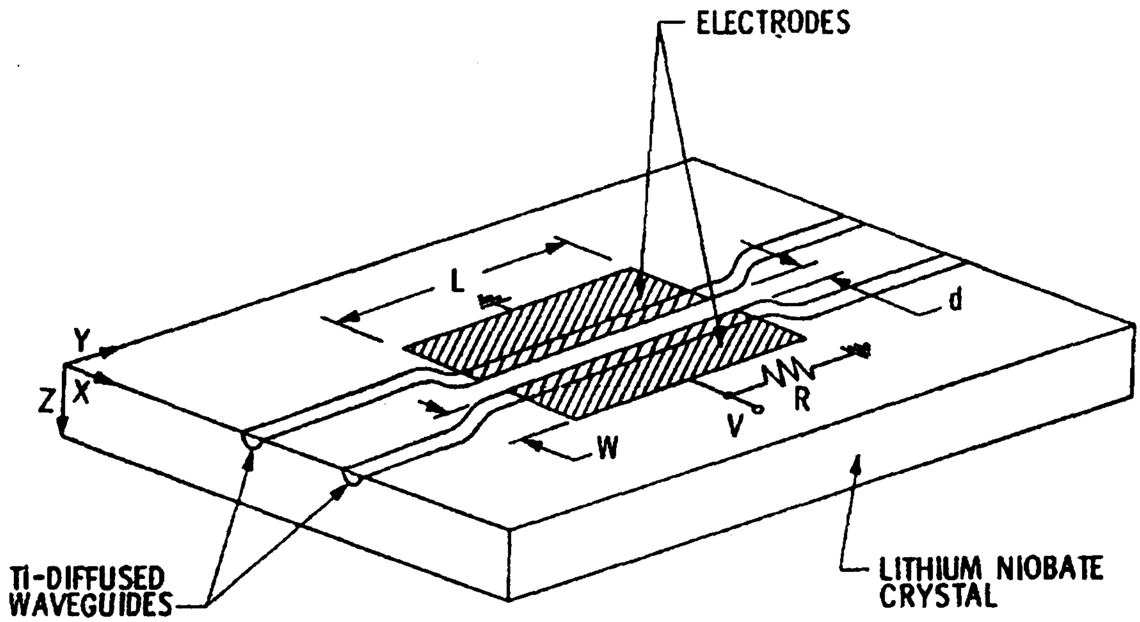

Fig ure 2. High speed directional coupler modulator.

II. OPTICAL SOURCES

Almost all solid state lasers and light emitting diodes (LEDs) can serve as the source for optical communications. However, due to the bulk negative resistance and high electron mobility of GaAs, and the low loss and dispersion of available quartz fibers, short wavelength AlGaAs sources emitting in the 0.8-0.9 μm spectral bands are now being used, while InGaAsP lasers emitting in the 1.2-1.6 μm wavelength range are developing for long distance and high bit-rate applications.

In fiber-optic communications, LEDs are used for short distance, low bit-rate systems because of their simpler drive circuitry, wider temperature range of operation, and higher reliability. Typical structures of fiber-optic LED, shown in Fig.3, are designed to have higher radiance with a light emitting area smaller than that of the fiber core to get efficient coupling. The state-of-the-art LED's are shown in Table I.

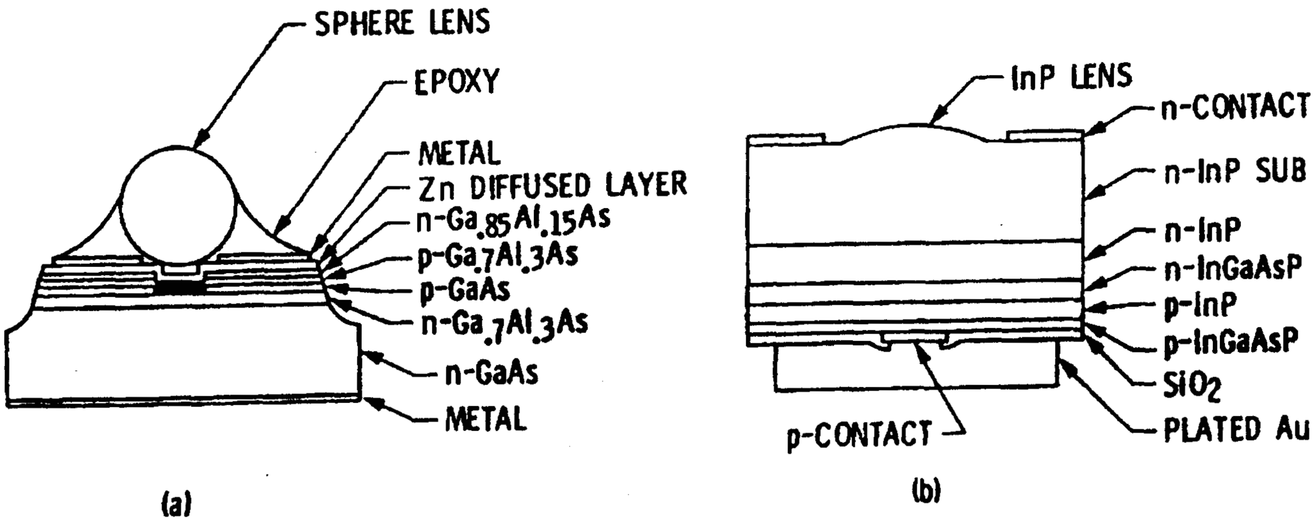

Figure 3. Typical Structure of fiber-optic LED's (a) AlGaAs LED, and (b) InGasAsP LED.

For long distance and high bit-rate applications, the vertically- or horizontally- double-heterostructure lasers were developed for reducing threshold currents and controlling the lasing mode suitably for coupling to fibers. The essential property required for fiber-optic use is the fundamental transverse mode. Both for short wavelength AlGaAs and long wavelength InGaAsP lasers, the stabilized transverse fundamental mode exhibits linear light output, low operation currents, high efficiency, high frequency modulation capability, and low noise. To stabilize the fundamental mode, optimization of the geometry and properties of the waveguide structure is essential.

Typical heterostructure lasers, involving semiconductor building blocks, for monolithically integrated opto-electronic circuits, are shown in Fig. 4. They consist of three main parts: active, cladding, and p-diffused regions. P-type and n-type layers form a diode. Once a current passes through the diode, electrons and holes are injected into the active layer, thereby increasing the amount of high-energy electrons and holes in that region. This results in an inverted medium whereby most of the charge carriers are in high energy states. As photons transverse this highly energetic medium, they stimulate it to emit more photons. Because the current passes through a narrow stripe contact, the injection is confined to a narrow region in the semiconductor crystal. The elements making up the cladding layer should be selected to provide high bandgaps and low refractive indices in order that electrons and holes are trapped in the active layer, and total internal reflection of the laser light occurs. The ends of the layer should be smooth so that light propagating in the laser's active layer will be partially reflected. As soon as the injected current passes a threshold level, the optical gain in the laser cavity is large enough to offset the optical loss due to the mirror's transmissivity. Increasing the current beyond the threshold contributes additional photons to the lasing mode, and a substantial optical power is emitted through the mirrors.

Table I The State-of-the-Art Optical Sources

Device		Wavelength (μm)	Power (mW)	Bandwidth (MHz)	Coupling Power* (mW)	Life Time (hr)
LED	AlGaAs	0.75 - 0.9	2	50	0.1	10^8
	InGaAsP	1.3	2	50	0.1	10^8
LD	AlGaAs	0.8 - 0.9	3 ~ 5	1000	1	10^6
	InGaAsP	1.3	3 ~ 5	1000	1	$>10^5$
	InGaAsP	1.6				

*Coupling Power to a fiber (core diameter : 60 μm, NA : 0.21)

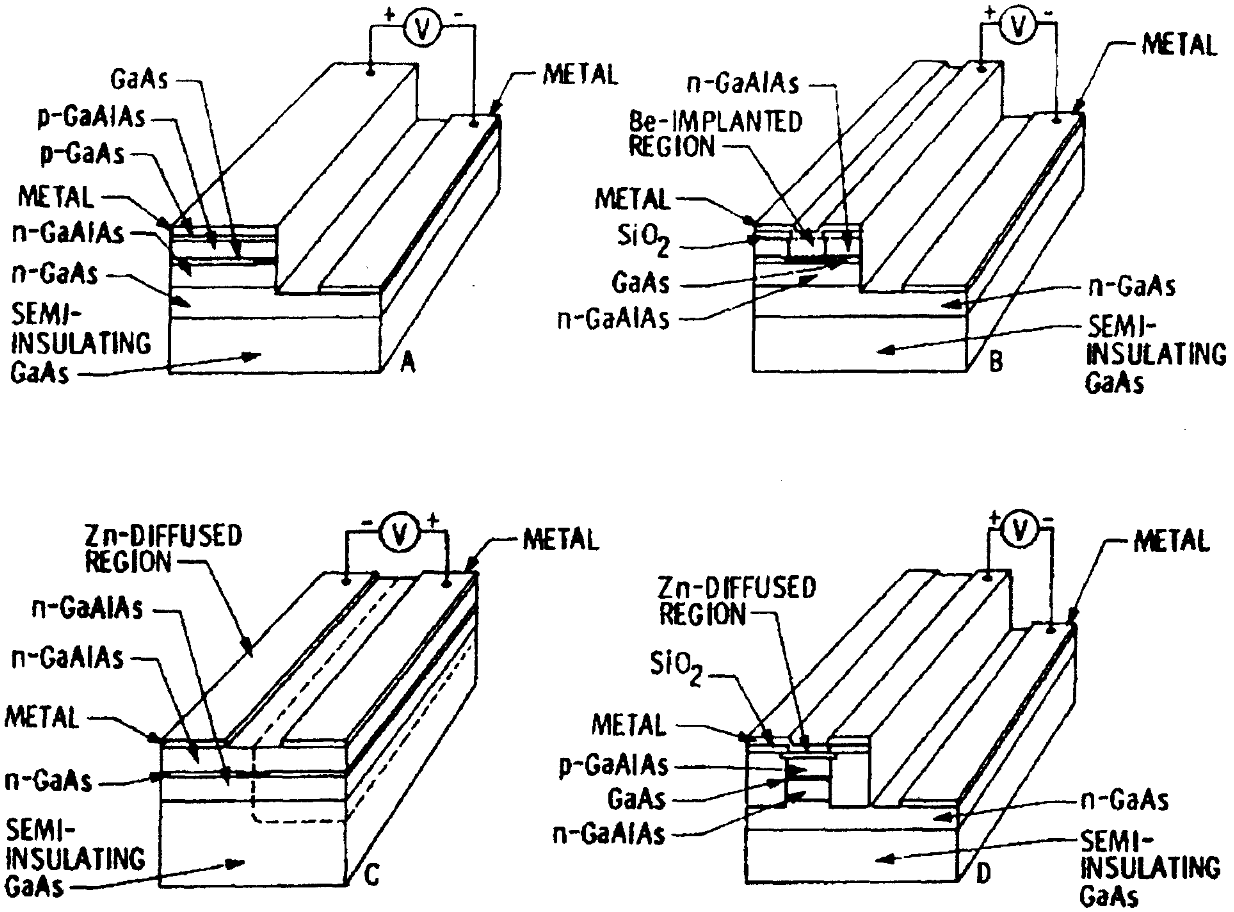

Figure 4. Four laser structures for optoelectric integrated circuits on a semi-insulating substrate confine the lasing to a narrow region. They include the "crowding effect" laser (A), a device with a beryllium-implanted region (B), and two devices, one with a zinc-diffused region (C), and the other with a buried heterostructure (D). Each has two metal contacts on top for connecting to a voltage source.

Diode geometry, catastrophic optical damage, relaxation oscillation, crystal defects, and the dielectric film coating, all affect the output power, signal modulation, noise, stability, and the laser lifetime. State-of-the-art lasers are shown in Table I.

The main degradation modes of laser diode sources are: dislocations that affect the inner region, metal diffusion and alloy reaction that affect the electrode, solder instability (reaction and migration) that affect the bonding parts, separation of metals in the heat sink bond, and defects in buried heterostructure devices. These modes are enhanced by current during ambient temperature operations. Facet damage due to oxidation is enhanced by light or moisture and is particular to laser diodes.

The main causes of degradation in the inner region is directionally dependent on the crystal structure as well as dependent on the material used for the source. In particular dislocations along the 100 direction grow as a result of interstitial atom or vacancy point defects. AlGaAs/GaAs show a much higher rate of dislocation growth than sources fabricated in InGaAs(P)/InP. In general, the longer the wavelength response of the material, the less sensitive it is to this point defect. Point defects can also lead to a slow degradation or a rapid degradation when the defect leads to a plane defect in the crystal structure. Improving crystal growth techniques is the only way of making them less likely.

Dislocations along the 110 crystal axis will grow and form as a result of mechanical bond stresses. The result of both types of dislocations are Dark Line Defects (DLD) and induce rapid degradation of the device. Another degradation in InGaAs(P)/InP sources is precipitation of host atoms that result in an elevation in pulse threshold current (driving current required for lasing). The higher this current is driven the faster degradation of other mechanisms will occur as a result as well as dark line defects. In looking for these types of degradation mechanisms it is more revealing to monitor the threshold current as opposed to the output power. The threshold current is more sensitive to defects than the output power. As the current is driven to saturation, noise will develop in the laser signal.

Oxidation of a source facet can lead to slow degradation. Sources that contain higher concentrations of aluminum tend to inhibit the oxide growth. Alumium particles are active and inhibit diffusion to the facet by decreasing the junction temperature. AlGaAs/GaAs sources will develop oxide thickness proportional to their output power levels when operating at low power and will grow thickness proportional to the square of the output power levels when operating at higher power levels.

Catastrophic Optical Damage (COD) occurs as a result of facet melting of the laser diode due to current concentration and optical absorption. Optical absorption that encourages non-radiative recombination results in heating and melting at the facet. The heat generated will also cause the bandgap to shrink and therefore as a result the current concentration increases creating more heat and the cycle continues.
The AlGaAs/GaAs sources are much more sensitive to this type of damage than the InGaAs(P)/InP sources. Where the first is considered unstable against oxidation and has high rates of facet oxidation, the second has a much lower rate of oxidation with respect to time and output power. The same is true for COD as the first will experience this at levels less than 1 MW/cm 2 the second will experience not until power densities of tens of MW/cm 2 have been reached. One solution to this is a non-absorbing mirror structure or NAM. The Japanese are working on fabricating this type of technology but it is difficult to manufacture at present.

In sources (and photodetectors) with alloy electrodes, there develops degradation as a result of the metal diffusing in towards the inner region. One example of an alloy type electrode is Au/Zn/Ni. During operation the metal will diffuse creating spikes along with the direction of current flow. The result is dark spot defects in the inner region of the semiconductor. The Schottky-type electrodes such as Ti/Pt/Au do not seem to cause the same degradation. The metal forms an inert interface with between the electrode and the semiconductor surface.

Soft-solders can reduce mechanical stresses on the bonding surface but tend to add to early degradation of the device. In, Sn, and Sn-rich Au-Sn are among the type of soft (low melting point) solders that are attributable to solder instabilities like whisker growth, thermal fatigue, void formation at the bonding part, and diffusion similar to what occurs with the alloy electrodes when in contact with the semiconductor surface. The instabilities directly lead to sudden premature failures. The higher melting point solders, or hard solders which include such materials as Au-rich AuSn eliminate many of the instabilities that plague devices that have problems with soft solders.

In Buried Heterstructure laser diodes (BH), the configuration and index of refraction changes nearby the active region of the laser diode creates a waveguide for light emerging from the interactions. This type of laser is considered an "index-guided" laser. The n-type InGaAsP active emitting region is surrounded on both sides by the p-type InP. The degradation mode in these lasers is associated with a breakdown or degradation of the active region due to a decrease in injected carriers. The degradation of the BH interface is considered a wear out failure and is not a sudden type failure. Above is a summary of the most generally common characteristics and degradation modes of laser diodes and LEDs. Facet degradation is specific to laser diodes. Some degradation modes can be eliminated through redesign of the semiconductor structures or through packaging techniques. For more information please refer ~~the~~ to references.[9-10]

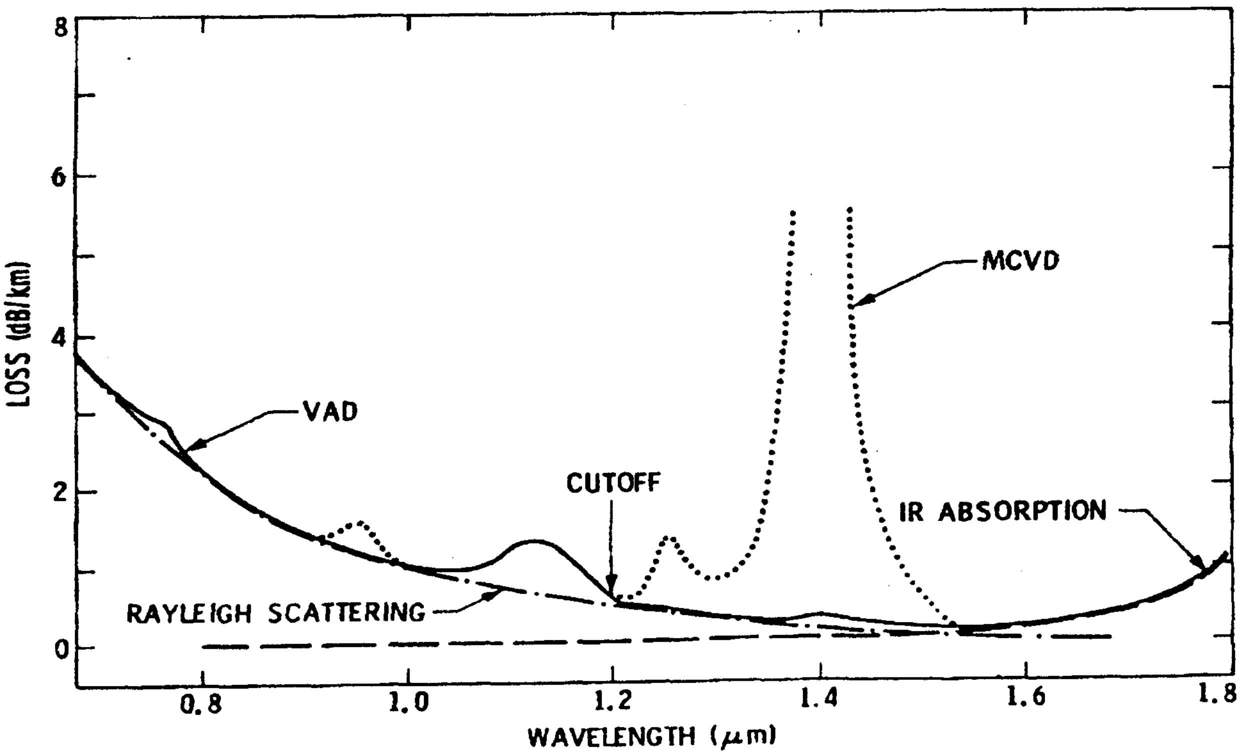

Figure 5. Typical loss in optical fibers.

III. OPTICAL FIBERS

Rapid progress in low loss, high bandwidth, single mode fibers holds promise for lighter, cheaper, and less noisy communications. The attenuation loss and the bandwidth are the main characteristics of the optical fiber. The transmission bandwidth is limited by multimode dispersion, as well as material and structural dispersion. The loss in quartz fibers is determined by Rayleigh scattering at short wavelengths and by intrinsic absorption of Si-O at longer wavelength, as shown in Figs 5. Efforts to develop a low loss fiber have concentrated on eliminating the aborption peak of 0-H ions at 0,95, 1.242, and 1.38 μm. Vigorous development is also underway on IR fibers such as fluorozirconate and fluorohafnate glasses for use at 7-8 μm in the IR to 0.2-0.3 μm in the near UV.

The well-known method for making quartz fibers involves modified chemical vapor deposition (MCVD) to achieve a low loss level of ~0.2dB/Km by reducing impurities. However, the appearance of a process-related index dip at the center of the fiber has encouraged the use of a new vapor-phase axial deposition (VAD) method to achieve bubble-free, 0-H ion free, single mode fiber[11] with a controllable *refractive* index. Table II shows the characteristics of the fiber made by this method.

Table II Comparison of VAD and MCVD Fibers

		VAD		MCVD	
Dimension of preform	typ.	10-20 km		2-5 km	
	max.	more than 100 km		about 10 km	
Speed of synthesis	typ.	0.4-0.7 g/min.		0.1-0.3 g/min.	
	max.	2-3 g/min. possible		0.5-1.0 g/min.	
Characteristics					
minimum loss (dB/km)		multi-mode	single-mode	multi-mode	single-mode
	0.85 μm	2.1	1.9	2.1	1.9
	1.3 μm	0.4	0.4	0.5	0.4
	1.55 μm	0.22	0.2	0.3	0.2
O-H ion conc.		less than 1 ppb		less than 10 ppb	
band width	typ.	0.5-1.0 GHz•km		0.8-1.2 GHz•km	
	max.	6.7 GHz•km		3.5 GHz•km	

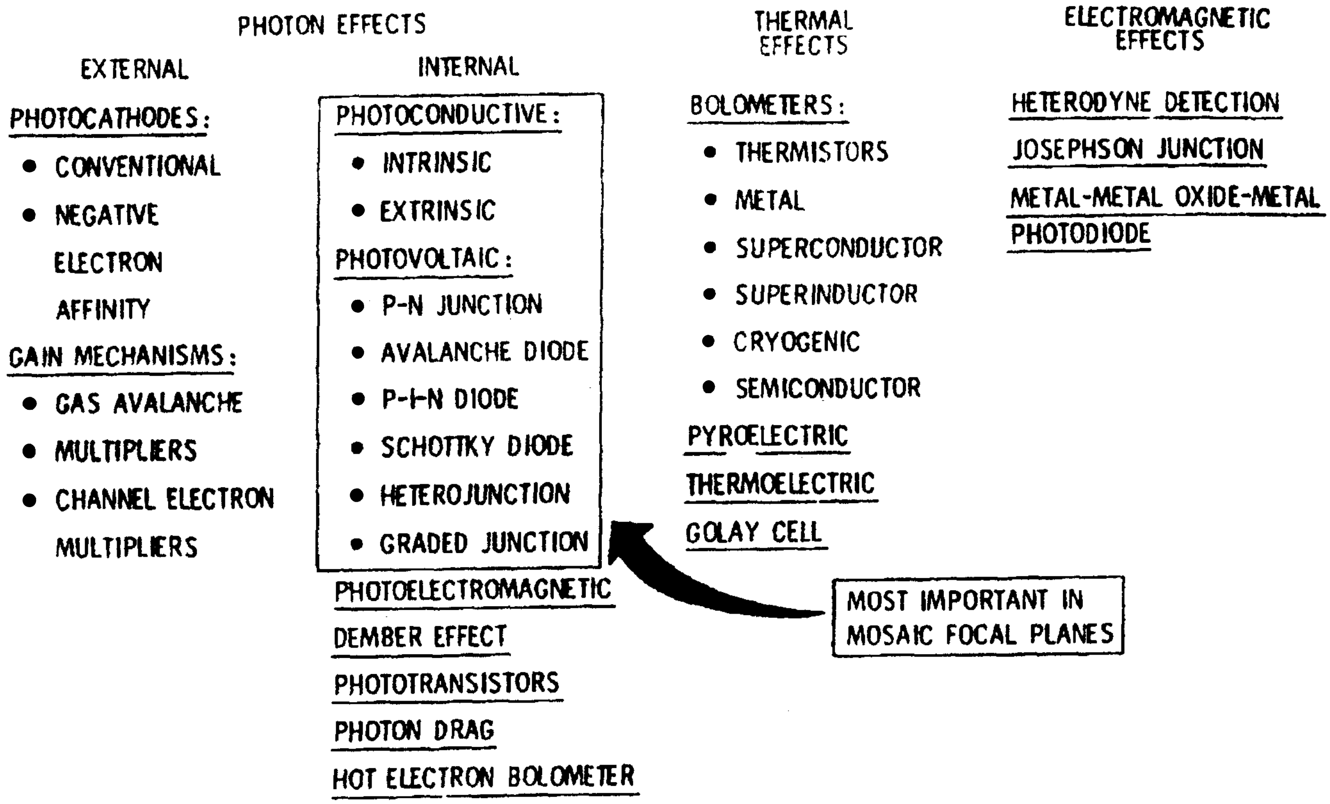

Figure 6. Classification of IR detectors.

IV. RECEIVERS

There exists a huge class of IR detectors available for use in different wavelength ranges as shown in Figs. 6 and 7. In order to be compatible with the newly developed optic fibers and sources, the two main types of integrated optoelectronic receivers are the junction photodiodephotogate, and photoconductive detector, and their arrays.

When light falls on the intrinsic region of a p-i-n photodiode, it generates electron-hole pairs which quickly separate, causing current to flow through the external circuit. If the voltage across the diode is fixed, one absorbed photon will cause one electron to pass through the external circuit. Thus, the quantum gain can be no more than unity for a p-i-n diode. However, with a sufficiently large reverse bias, a junction photodiode can have a higher quantum gain. Such a bias causes a large electric field, which in turn, imparts enough energy to an electron to create new electron-hole pairs upon impact (impact ionization). A single electron-hole pair can thus cause an avalanche of pairs. As a result, a single photon can cause many electrons to flow in the external circuit in this avalanche photodiode (APD).

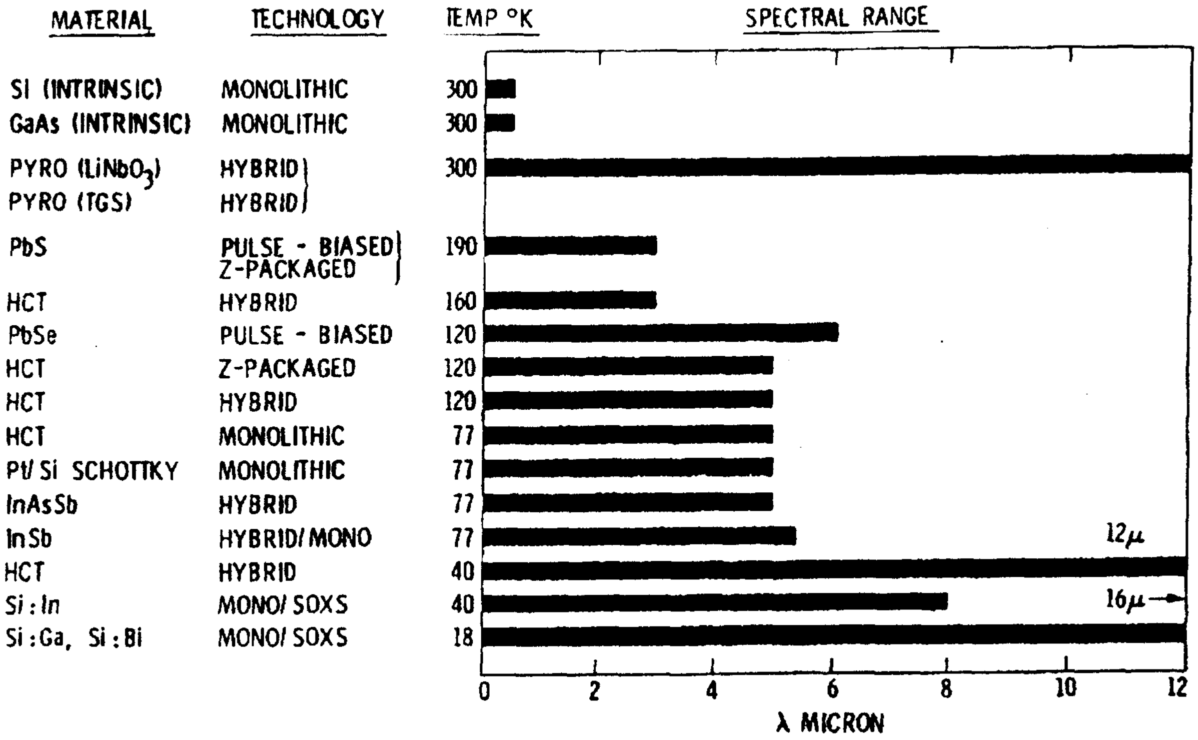

Figure 7. Current focal plane materials, temperatures, and characteristics.

Table III The State-of-the-Art Detectors

	Si-APD	Ge-APD	InGaAs/InP-APD	InGaAs-PD/FET
λ (μm)	0.5-1.0	0.8-1.5	1.25	1.0-1.7
η max	0.8	0.8	0.8	0.8
i_d (A)	-10^{-11}	-10^{-6}	-10^{-9}	-10^{-9}
C_j (pF)	-1	-1	-1	-2
F (M)	-3(M=100)	-7(M=10)	-3(M=10)	
τ_r (ns)	0.15		0.16	0.06

A representative photoconductive detector is simply a semiconductor with a contact attached to either side. When the light falls on the detector, the creation of electrons and holes lowers the resistivity of the material, If the Voltage across the detector is kept constant, the reduced resistivity causes an increase in the detector's current. Because the semiconductor always neutralizes excess holes with an equal number of electrons, the number of electrons that flow in the external circuit per absorbed photon depends on the lifetime of excess holes in the material. If many electrons can traverse the crystal before recombine with holes the detector will have a quantum gain larger than unity.

Si and Ge p-i-n photodiodes and avalanche photodiodes are well developed for short and long wavelength, high bit-rate applications. Since the same property that makes AlGaAs an efficient optical source also makes it an efficient optical detector, by adjusting the stoichiometry, photons emitted by $Al_xGaI_{1-x}As$ will be absorbed by $Al_yGI_{1-y}As$ so long as y is no greater than x. This improves the device integration because of the possibility to combine lasers, detectors, and active electronic devices on the same crystal chip of GaAs. A low dark-current, high-gain InGaAs/InP APD has been developed for use in the 1.0-1.6 μm spectral region[12], while a receiver using a low dark-current AlGaAs p-i-n photodiode and a low noise GaAs FET was designed for long wavelength transmission[13]. Table III shows the operating characteristics of typical detectors.

V. OPTICAL AMPLIFIERS

High speed waveguide intensity modulations are essential components to allow utilization of the large bandwidth of single-mode fibers. However, direct current modulation of semiconductor lasers presently offers a maximum 1-2 GHz bandwidth due to the carrier lifetime limitations[14]. Furthermore, in most semiconductor lasers, fast current modulation also results in an undesirable wavelength modulation which would be detrimental for wavelength multiplexing.[15]

On the other hand, external single-mode waveguide devices, which provide efficient, low crosstalk optical switching, high speed time division multiplexing or modulation, wavelength multiplexing and demultiplexing, and polarization manipulation have been demonstrated.[16] An optical switch and modulator with ~100 ps switching time and a traveling wave phase modulator with modulation bandwidth approaching 10GHz have been reported, An on/off modulator is simpler than a 2x2 switch because only a single output port is required. Polarization insensitive switches, modulators, and filters have been realized. However, since suitable laser diode materials are not presently compatible with detector materials, near term waveguide applications will be hybrid integrated devices. Optical waveguides, components, and devices have been fabricated in various materials, using a variety of techniques such as sputtering, chemical vapor deposition, liquid phase epitaxy and diffusion, ion implantation, and ion exchange. For many integrated optical devices, LiNbO3 remains the prime candidate because of its excellent piezoelectric, electro-optic, and waveguiding properties.

A possible important element in integrated optical devices is the directional coupled waveguide which consisted of a pair of closely spaced identical strip waveguides as shown in Fig. 2. Light input to one waveguide couples into the second as a result of the overlap in the field of the two guides. The coupling per unit length depends upon the waveguide parameters, the interwaveguide gap, d, and the guided wavelength, x, The directional coupler is also characterized by the difference in propagation constants between the two waveguides, $\Delta\beta = 2\pi/\lambda\ (n_2 - n_1)$, where n_1 and n_2 are the effective indices, and by the interaction length L. The phase mismatch can be adjusted via the linear electro-optic effect (r) by application of voltage (V) to the electrodes along the side of the waveguide. In this case, for Z-cut lithium niobate,

$$|\Delta\beta| = (2\pi/\lambda)\ \alpha\ n_e^3\ r_{33}\ ^{V/d} \tag{1}$$

for TM mode light polarized in the Z direction. α is the overlap integral, a number between zero and one which is a measure of the overlap between the applied electric field and the optical field intensity within the waveguide. To the first order, the applied field produces only small changes in the coupling. Vigorous research is underway to develop improved waveguides which eliminate various problems such as d.c. drift related to the fabrication.

$LiNbO_3$ waveguides with silicon overlays are emerging as a basic building block for a variety of integrated-optic components. However, the development and optimization of these devices are, in large part, hindered by the lack of understanding of the specifics of the Si-on-$LiNbO_3$ structure which appears to differ dramatically from those of the Si and $LiNbO_3$ wave guides, considered separately.[17] Planar light-wave circuit (PLC) hybrid integration seems to be a promising way to utilize low-cost and highly functional optical components which are integrated with optoelectronic (OE) devices. As low-cost components, wavelength-division-multiplexing (WDM) hybrid tranceiver components, a multi-wavelength light sources, a high-speed optical wavelength selector and a differential photo-receiver modules have been demonstrated to construct optical transmission and switching systems employing dense WDM and time-division-multiplexing(TDM) techniques in future optoelectronic integration technology.[18]

VI. COUPLING AND SPLICING

The ability to efficiently couple light between a single mode fiber and a strip waveguide, and to splice fibers is essential for integrated optoelectric devices. Fusion methods and butt joint methods involving adhesion to the fiber core of similar refractive index materials are common techniques for splicing fibers with a loss less than 0.1 dB[19]. End-fire coupling between fibers and Ti-diffused LiNbO3 waveguides have been studied to minimize the coupling loss by adjusting the diffusion parameters and maximizing the overlap between the modal fields of the waveguide and fiber. The reflection loss can be reduced by use of antireflection films. Minimizing the coupling loss is still in the experimental stage. The abrupt decay of the optical field at the crystal surface, due to the large index discontinuity and the mode mismatch between the circulary symmetric fiber and the vertically asymmetric waveguide, are the primary sources of loss, assuming perfect geometric alignment. Total throughput losses of ~ 3dB at 0.63 μm and 1.15 μm have been reported.[20]

The properties of optical fibers are much superior to that of the microwave transmission line. On the other hand, the laser is no better than the microwave oscillator in coherency and stability at present. Pure single mode lasers, stable multimode lasers, and improvement in the temperature dependence of the threshold current for long wavelength lasers needs to be achieved, together with further development of connectors, switches, filters, isolators, and coupling devices.

VIII. FURTHER RELIABILITY CONCERNS

The good news for the optoelectronic and photonic devices is that this technology is developing very rapidly. The bad news from our reliability perspective is that there are no low cost sources, new or surplus, for these devices as far as reliability in space applications.

Note that most high power diode lasers are near IR - often around 800 nm for pumping lasers and optical communications. High power visible laser diodes are much less common and usually limited to less than a W at 670 nm. Obtaining the diode is only a small part of the problem. These devices are exceeding fussy about drive and cooling - even much more so than the little laser diodes found in CD players and laser pointers. And, needless to say, at these power levels, users' eyes (and flammable objects) don't get a second chance - laser safety must be at the top of the reliability list.

Table IV. Summary of most common failure modes.

Following are the list of the most common failure modes of the optical communication devices reported in literatures:

Surface Degradations
Facet oxidation/slow
Aluminum/inhibit diffusion: AlGaAs/GaAs
Output power: 200mW
Catastrophic optical damage/fast
Facet melting: AlGaAs>InGaAs/InP
Bandgap shrinking: non-absorbing mirror (<0.1 MW/cm^2)
Alloy electrodes
Metal diffusion
    AuZnNi: Dark spot defects
Schottky type electrode: TiPtAu
Bonding parts
    Soft solders: In, Sn, and Au rich solders/sudden failures
    Hard solders: Au rich solders/reduce instability
Optical degradation/Modes
Dislocations
Metal diffusion

Oxidation
Inner material Degradations
Point Defects
Crystal structures vacancies
AlGaAs/GaAs>InGaAs(P)/InP
Quality of the Crystal
110 Crystal axis
Impurity level of the material
Workmanship/reproducibility
Radiation Damages
Total Ionizing Dose (25K Rad)
Replacement Damage (>25K Rad)
Single Event Upsets (75MeV/mg/cm^2)
Single Event Latch ups
Single Event Burn outs
Single Event Gate Ruptures.

Major parts of the optoelectronic and photonic devices:

Single mode fibers
Multi-mode fibers
Optical wave guides: decreased injected carriers
Index guided: p-InP/n-InGaAs/p-InP
Light Emitting Diodes
Laser Diodes
Single mode diode lasers
Multi-mode diode lasers
PIN receiver diodes and transistors.

Major critical variables to define the failure modes are:
Lifetimes
Operating Temperature (100 °C, 10° C/half life): τ= exe (E_a / kT)
Bias Current/Voltage
Output power
Data Rates: 50Mb/s
Spectral width.

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